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Magnetic Microcalorimeter Gamma Detectors for High-Precision Non-Destructive Analysis

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2014 Annual Report

MAGNETIC MICROCALORIMETER GAMMA DETECTORS FOR HIGH-PRECISION NON-DESTRUCTIVE ANALYSIS

Project number LL12-MagMicro-Pd03

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1. INTRODUCTION

Cryogenic gamma (γ) detectors with operating temperatures of ~0.1 K offer 10× better energy resolution than conventional high-purity germanium detectors that are currently used for non-destructive analysis (NDA) of nuclear materials. This can greatly increase the accuracy of NDA, especially at low-energies where gamma rays often have similar energies and cannot be resolved by Ge detectors. Among the different cryogenic detector types, Magnetic Micro-Calorimeters (MMCs) have the potential of faster count rates and better linearity. High linearity is essential to add spectra from different pixels in detector arrays that are needed for high sensitivity.

MMC gamma detectors measure the energy of absorbed gamma rays form the resulting change in magnetization of an erbium-doped gold (Au:Er) sensor. The signal is read out with a SQUID preamplifier and processed digitally with room temperature electronics (see inset figure 2). The objective of this project is to develop ultra-high energy resolution γ-detectors based on magnetic micro-calorimeters (MMCs) for accurate non-destructive isotope analysis (NDA). Since MMCs, like other cryogenic γ-detector technologies with operating temperatures <0.1 K, are intrinsically slow and have to be small for high resolution, special emphasis will be placed on questions that determine sensitivity and the potential for scaling to arrays. Objectives for FY14 were therefore to fabricate an improved version of MMC γ-detectors and test their energy resolution, maximum count rate, readout noise, crosstalk between pixels and linearity.

2. DETECTOR FABRICATION

Earlier MMC γ-detectors were fabricated by depositing the Au gamma absorber directly onto the magnetic Au:Er sensor. Their energy resolution was limited by varying amounts of energy loss into the substrate. We have sent our graduate student Cameron Bates to work with our collaborators at the University of Heidelberg and fabricate the next generation of MMC gamma detectors. In these detectors the absorber is supported on Au posts, so that the energy is fully thermalized in the Au absorber before reaching the Au:Er sensor. The input to the SQUID preamplifier consist of two coils in a gradiometer configuration with different polarity windings, so that each sensor has two pixels that produce signals with opposite polarity.

3. REFRIGERATION

We have optimized our liquid-cryogen-free adiabatic demagnetization refrigerator (ADR) so that it reaches a base temperature of ~35 mK. The ADR does not require any cryogenic liquids, and its cool-down is fully automated. While a base temperature of ~35 mK is sufficient for the goals of this proposal, namely to attain an energy resolution <100 eV, the ADR requires periodic cycling to 4 K every ~8 hours, which makes long data acquisition from weak radioactive source cumbersome. We have therefore started a collaboration with Peter Shirron at NASA Goddard to build a continuous adiabatic demagnetization refrigerator (CADR) that can keep MMC gamma detectors at a temperature of ~35 mK indefinitely. In addition, the availability of a dilution refrigerator with a base temperature <20 mK would be very desirable for future projects.

4. GAMMA SPECTROSCOPY RESULTS

4.1 SPECTRA FROM HEIDELBERG

The improved detector fabrication process has directly led to a significant improvement in energy resolution. We have tested the new MMCs with our collaborators at the University of Heidelberg in a dilution refrigerator with a base temperature of 18 mK. The gamma-rays from the Am-241 source were collimated onto the MMC detector with a Pb pinhole, the full signal waveforms were captured and processed with an optimum filter. The measured energy resolution of 46 eV FWHM is the best resolution ever obtained with an MMC gamma detector (figure 1). As expected, the line-broadening at higher energies is greatly reduced due to full thermalization of the gamma energy in the Au absorber.

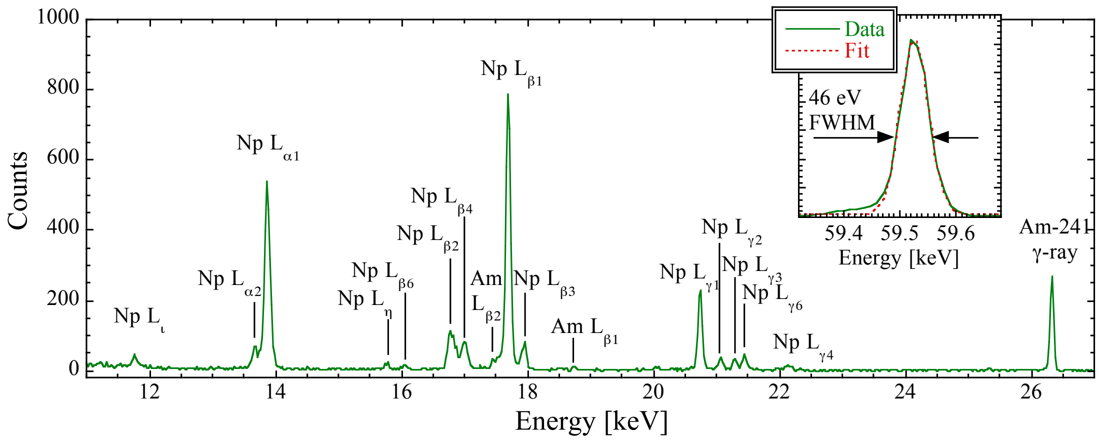


Figure 1: High-resolution Am-241 spectrum taken with one of our new MMC gamma detectors in a dilution refrigerator at a temperature of 18 mK at the University of Heidelberg

4.2 SPECTRA FROM LLNL

We have repeated the measurements at LLNL in our ADR cryostat with a base temperature of only ~35 mK, which significantly decreases the signal height and therefore the energy resolution. Figure 2 shows the detector response to a Pu-242 source. We have selected this source for a demonstration experiment because the direct detection of Pu-242 in a mixed-isotope Pu samples, (which cannot be done with a Ge detector,) would be of great interest for the safeguards community. Full waveforms were captured and filtered digitally. During the detector testing, we have taken 32 spectra from the two pixels of our MMC gamma detector, calibrated them linearly and added them with 20 eV bins. The energy resolution of this combined spectrum is 150 eV FWHM, although individual spectra have a resolution as good as 130 eV FWHM at 60 keV.

More importantly, the response of the MMC gamma detector is very linear. This is crucial because adding the response from different pixels is essential for cryogenic detectors, because the individual pixels are so small and the sensitivity can only be increased by fabricating detector arrays. For example, the 32 individual spectra that contributed to figure 2 were calibrated using the strong lines below 60 keV only. Still, after summing all the spectra, the weaker lines in the 100 keV region emerge with the same high energy resolution as the low-energy lines, indicating a high level on linearity. This is also demonstrated in the plot of the residuals to the linear fit (figure 3), which are below 10 eV. (In the past, we could never fabricate transition edge sensor (TES) microcalorimeter gamma detectors with the same level of linearity. As a consequence, the TES energy resolution always decreased when adding spectra from different pixels.)

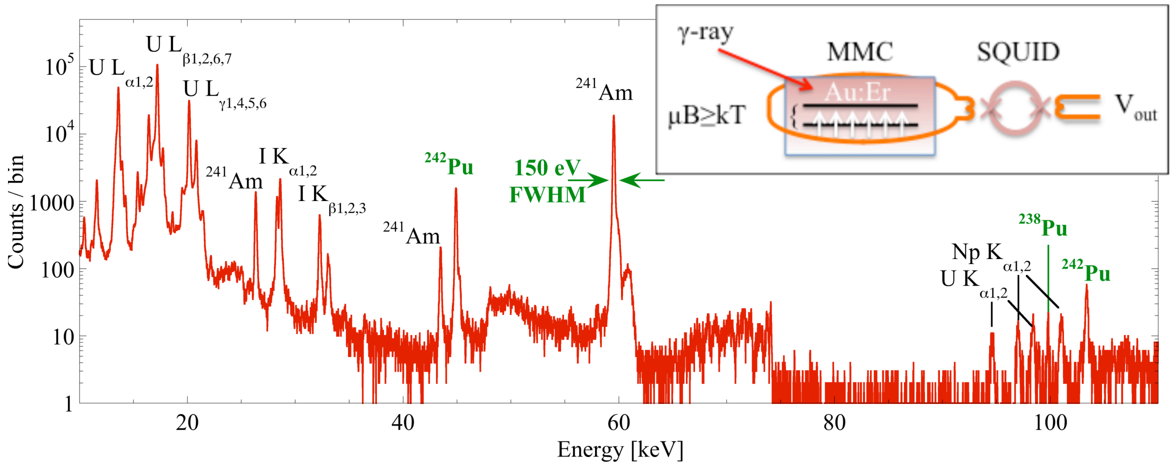
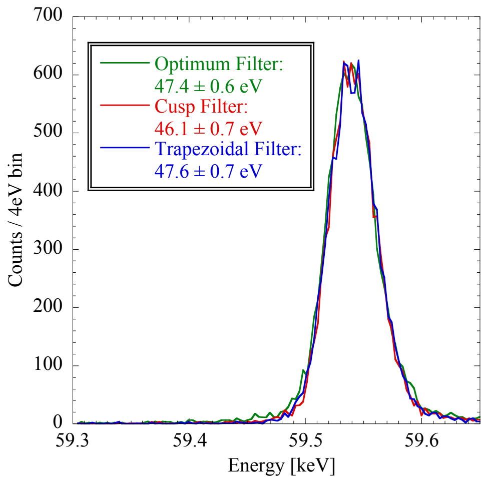


Figure 2: Sum of 32 spectra from a Pu-242 source, taken with the same gamma detector as above in our ADR cryostat at LLNL at a higher temperature of ~35 mK.



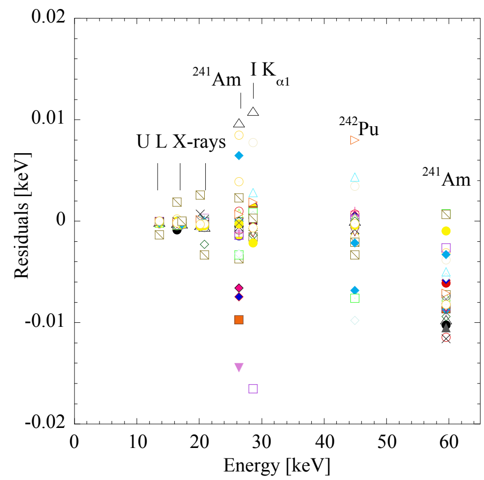


Figure 3 (left): Our trapezoidal filter routine produces the same high energy resolution with the Heidelberg data from figure 1 as the optimum filter (which are only "optimum" for identical signal shapes and stationary noise). Figure 4 (left) The residuals to a linear fit of the 32 spectra that went into figure 2 are extremely small.

5. PATH FORWARD

The path forward should aim at improving the performance in single pixel MMC gamma detectors, and at developing arrays of MMC detectors to improve sensitivity. For improved energy resolution, a dilution refrigerator with a base temperature <20 mK would be very desirable (cf. figures 1 and 2). For improved speed, a better coupling of the sensor to the cryostat base temperature must be pursued. For improved sensitivity, detector arrays should be developed. Since the multiplexing technology for MMC detectors is not very mature (yet), the arrays readout should initially be pursued by parallel readout of individual MMCs.

6. PUBLICATIONS

"Development of MMC Gamma Detectors for Nuclear Analysis", C. R. Bates, C. Pies, S. Kempf, L. Gastaldo, A. Fleischmann, C. Enss, S. Friedrich, *J. Low Temp. Phys*. **176**, 631–636 (2014)